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Research paper

Combined control of secondary air flaring angle of burner and air distribution for opposed-firing coal combustion

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HIGHLIGHTS

- We propose a novel combustion adjustment method with burner flaring angle.
- We combine burner flaring angle with air distribution to control combustion.
- The effect of combustion adjustment on temperature distribution is studied.
- The burnout and NO_x emission are improved through combination adjustment.

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ABSTRACT

A novel swirl burner with adjustable inner secondary air flaring angle β is proposed and tested in an opposed fired pilot-scale furnace. The influences of five different flaring angles (β = 11.4/17.1/26/31.7/35.5) are studied on combustion and emissions under different air distributions. Two different rank coals are used. Changing β with air distribution helps coal ignition and promotes burning temperature level. Low-rank coal requires larger β for ignition and burning fiercely than high-rank coal. Enlarging β to 31.7° helps to decrease CO emission effectively. The specific β corresponding to a certain air distribution can limit NO_x emission further. The high burnout of two coals corresponds to different β of burner. Inner secondary air flaring angle variation, combining with air distribution adjustment, can improve coal adaption, and help burning more effectively and cleaning.

1. Introduction

Coal combustion plays an important role in world energy consumption. Especially in China, coal constitutes approximately 60% of primary energy resources and is the dominant fuel in power plants. The coal-fired power generation still accounts for above 75% proportion of total installed capacity in China [1]. At present, wall fired, tangential-fired and W-flame fired are the three most popular combustion technologies applied in power plants [2–10]. Wall fired boiler is widely used because of its flame organization independence, unlimited boiler shape and little gas temperature deviation in the horizontal flue gas pass. However, flame stability at low load and NO_x emissions are still the main concerns in design and operation [11]. Novel swirl coal burner technology presents an efficient method to solve these problems by enhancing ignition and staged combustion. Swirl burner has become the focus of researchers in recent years. A. Giannadakis [12] investigated a swirling jet under the influence of a coaxial flow and discussed complex bubble in the flow field. M.A. Nettleton [13] discussed the influence of swirl angles on flame stability in pilot-scale plant. Šarlej demonstrated an application of computational fluid dynamics in burner design and optimization [14]. Zhou [4] researched the influence of primary air pipe of a low NO_x swirl burner on combustion characteristic. Jing [15] operated experimental study on outer secondary air vane angle. Li [11] proposed a new low-NO_x burner technology with centrally fuel rich coal combustion burner. These literatures focused on the burner structure modified and innovations. Air distribution adjustment is also an effective way for burner to improve or change combustion conditions in power plant. Anil Purimetla [16] performed computational studies on the secondary air flow of the burners to assure proper balance and optimization. Jing [3] studied the effect of primary air ratio on combustion and NO_x emissions. A.S. Veríssimo [17] investigated the inlet air velocity importance on

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Nomenclature

IPA	inner primary air
OPA	outer primary air
ISA	inner secondary air
OSA	outer secondary air

Symbols

a	depth of furnace (m)
ρ	density (kg/m^3)
u	axial velocity (m/s)
x, y, z	depth, width and height coordinate of the furnace (m)
X, Y, Z	dimensionless depth, width and height of the furnace (-)
t	gas temperature (°C)
β	inner secondary air flaring angle (°)
w	mass fraction (%)
ψ	char burnout

Subscripts

1/2,3/4	inner/outer primary air, inner/outer secondary air
k	input coal
x	char sample
opt	optimization

flameless combustion establishment. A. González-Cencerrado [18] studied the pulverized fuel flame characteristic under different swirl numbers. In recent years, the effect of coal concentration variation in primary air of burner on NO_x reduction is discussed [19,20]. However, the study on the flaring spout, which is commonly used in the swirl burner and has significant impact on combustion characteristics, is little reported.

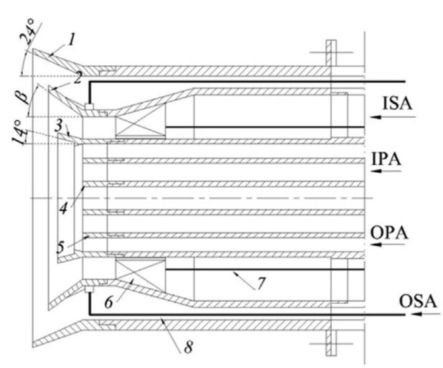
In this work, a novel swirl burner with adjustable inner secondary air (ISA) flaring based on dual-register burner structure is proposed. The combustion technology of integrating ISA flaring angle modulation and the traditional air distribution adjustment is explored through combustion experiment. From the result we try to understand how the flaring angle and air distribution affect coal combustion. Combustion efficiency and pollution emission are also comprehensively discussed in this paper.

2. Novel burner and experimental setup

Flaring angle of swirl burner is proved to influence reflux and flow characteristic outside the spout [21,22]. This novel burner proposed in our work replaces the traditional stationary flaring with adjustable flaring composed of circumferential stacked steel sheets, which is shown in Fig. 1. It realizes real time adjustment of the flaring angle to satisfy different combustion needs.

There are four layers in the burner to supply combustion air, which are inner/outer primary air and inner/outer secondary air, separately. Only inner secondary air is rotary jet caused by axial swirl vanes. The adjustable ISA flaring is comprised of 24 partial overlapping multi-flakelets circumferential distribution on the end of inner secondary air straight pipe. Pins are used to connect the adjustable flaring and straight pipe so as to rotate the flakelets and vary flaring angle. Each flakelet fixes one linkage on the back with pin seal. All the linkages are connected by a lantern ring. Two steel rods are separately fixed on the lantern ring symmetrically. The flaring angle β can be changed through pulling or pushing the steel rods.

(a) Burner spouts of three different ISA flaring angles



1. outer secondary air flaring; 2.adjustable inner secondary air flaring; 3.outer primary air; 4.center air pipe; 5.inner primary air pipe; 6.swirl vanes; 7.steels rods of swirl vane; 8.steel rods of adjustable ISA flaring

(b) Burner structure

Fig. 1. Novel swirl burner with adjustable inner secondary air flared pipe.

A laboratory-scale furnace with opposed wall fired type is built. Fig. 2 shows the schematic combustion system where the novel burner is studied. This test system is composed of furnace body, measurement system, coal supplying system, air supplying system, and cooling system. Two swirl burners are symmetrically installed on the front and rear wall separately. The lower furnace called burner zone with a cross sectional area of 1.00 m × 0.80 m is surrounded by refractory bricks with a thickness of 0.5 m for heat preservation and insulation. The upper furnace called burnout zone with a height of 1.15 m and a cross sectional area of 0.50 m × 0.80 m locates above the second platform for burnout. The oil gun is used to ignite the pulverized coal before experiment. The primary air and secondary air rate into the furnace are monitored through calibrated back to back pitots with an accuracy of ±3.5% and controlled by valves.

In the combustion experiment, thermocouples and water-cooled stainless probes are inserted through measuring holes to a specific depth to obtain gas temperature, species composition and fly ash sample. The flue gas temperature in burner zone is measured with water-cooled PtRh10-Pt thermocouple. The burnout zone gas temperatures are measured with NiCr-NiSi thermocouples nested in the porcelain sleeves. These two thermocouples are calibrated with relative error of 0.75% |t|. The GASMET-DX4000 flue gas analyzer is used to measure gas species with an accuracy of ±2 vol%. The oxygen component is monitored by the MSI-Compact flue gas analyzer with an accuracy of ±0.3 vol %. The unburned carbon is investigated by gravimetric determination method using fly ash sampling. Pulverized coal is supplied by four spiral micro-quantity feeders and controlled quantitatively through motor speed. The total feeding rate of pulverized coal keeps thermal power input constant for 0.7 MW. The fuel characteristics are detailed in Table 1.

A system of rectangular coordinate is built for the laboratory-scale furnace to unify locations of combustion space. The mid-

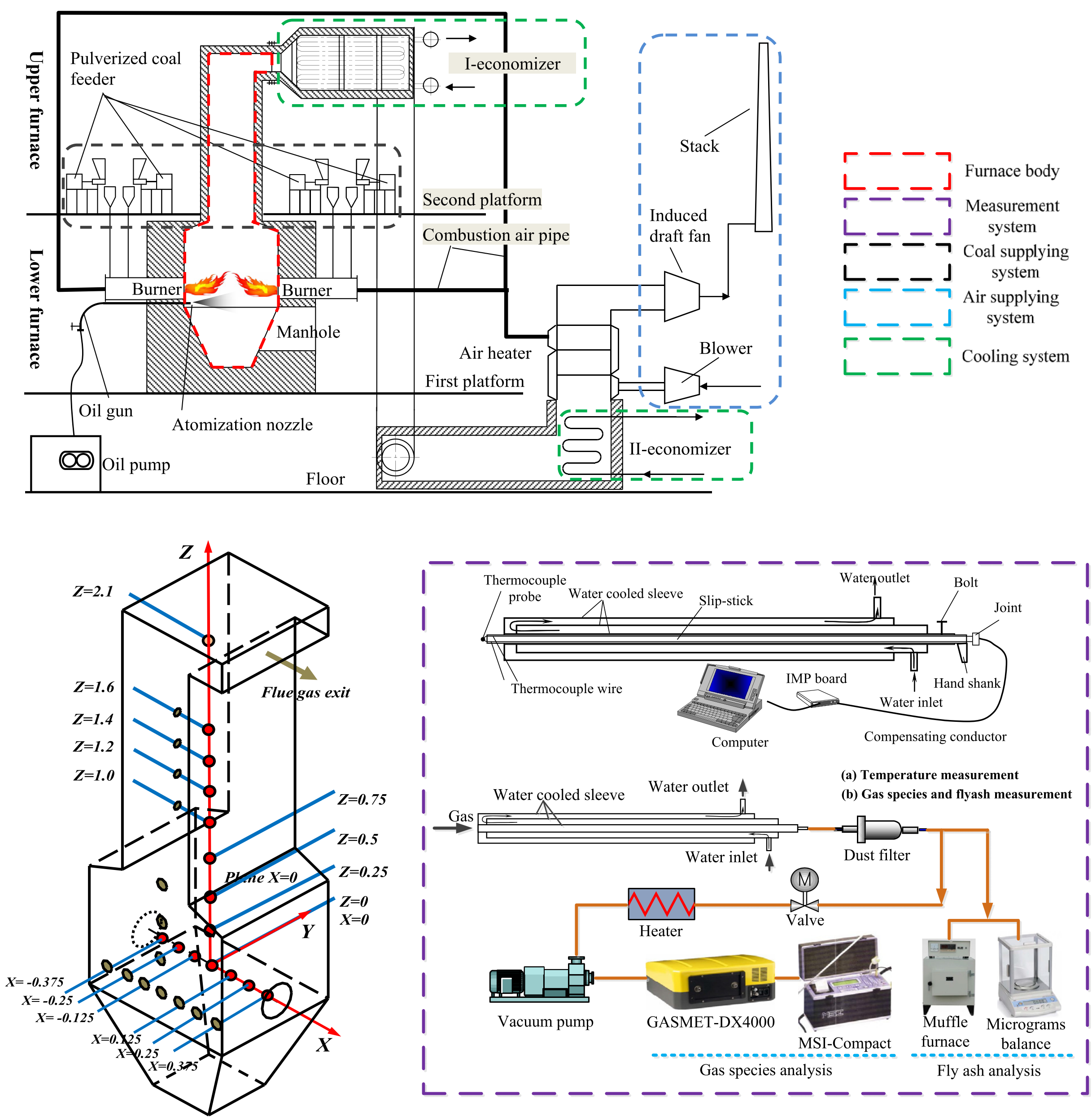


Fig. 2. Combustion experiment system.

point of burner axis is selected as the origin of the coordinate. The dimensionless depth, width and height of furnace are separately defined as $X = x/a$, $Y = y/a$, $Z = z/a$, where a is the depth of furnace as a reference size.

The air inlet momentum impacts on the flame obviously [17]. Considering the major role and adjacent position relation in primary air and secondary air, the momentum ratio of inner secondary air to outer primary air is defined as follows, which can be used to non-dimensionalize all the air distribution conditions [23].

$$M = \frac{\rho_3 u_3^2}{\rho_2 u_2^2} \tag{1}$$

where ρ_2, ρ_3, u_2, u_3 represent the density of outer primary air and inner secondary air, the axial velocity of outer primary air and inner secondary air, respectively.

The study conditions are displayed in Table 2, which mainly focuses on the effect of ISA flaring angle and air distribution of the swirl burner.

3. Results and discussion

3.1. Impact on coal ignition

For opposed wall fired combustion, pulverized coal from burner first flows in the furnace depth direction, and then moves upwards in the furnace height direction. Therefore, the burner axis temperature indicates coal ignition characteristic. The temperature distribution in the burner axis direction is compared in Fig. 3–4.

Under each air distribution, the temperature level and growth gradient away from the burner can be changed by shifting ISA flaring angle. When the momentum ratio of inner secondary air to outer primary air, M, becomes larger, the influence of ISA flaring angle on burner axis temperature appears more notable. Under $M = 6.09$, increasing β lifts temperature near the burner which benefits pulverized coal ignition. That is because large β enhances the swirling of inner secondary air and increases reflux of hot gas from furnace center. On the condition of $\beta = 31.7$, the measuring point near the burner shows highest temperature level. The corresponding condition is suggested for ignition. If continue to increase β, the temperature level drops then. There is an optimum β for improving coal ignition under a certain air distribution as Fig. 3 shows. Overlarge β leads to complete diffusion air flow outside the burner [24] which may result in lower reverse flow rate in the center reflux zone. This flow pattern of rotational jet is disadvantageous to hot gas reflux and coal particle ignition [25].

Table 1
Coal properties (as received).

Name/Coal type	Huangling (HL)	Wuhai (WH)
Proximate analysis (by weight), %		
Moisture	6.8	1.39
Ash	13.59	43.94
Volatiles	30.25	17.54
Fixed carbon	49.36	37.13
Ultimate analysis (by weight), %		
C	65.67	42.87
H	3.95	2.70
O	8.6	8.01
N	0.85	0.66
S	0.54	0.43
Q_{net} MJ/kg	24.925	16.29
Particle size distribution		
Fineness (R_{90})	77.1	70.1
Mean diameter (μm)	137	115

Table 2
Burner parameter and study conditions.

Num	Parameter	Variable symbol	Unit	Value
1	Air ratio	V_1	–	$f_1 = 0.1, f_2 = 0.1, f_3 = 0.6, f_4 = 0.2, M = 6.09$
		V_2		$f_1 = 0.1, f_2 = 0.1, f_3 = 0.5, f_4 = 0.3, M = 4.23$
		V_3		$f_1 = 0.1, f_2 = 0.1, f_3 = 0.4, f_4 = 0.4, M = 2.71$
		V_4		$f_1 = 0.15, f_2 = 0.15, f_3 = 0.35, f_4 = 0.35, M = 0.92$
2	Swirl number	n	–	$n_1 = 0, n_2 = 0, n_3 = 0.95, n_4 = 0$
3	OPA flaring angle	β_{OPA}	°	14
4	ISA flaring angle	β	°	11.4, 17.1, 26.0, 31.7, 35.5
5	OSA flaring angle	β_{OSA}	°	24
6	Air temperature	T_0	K	343
7	Dense(inner)/ Dilute(outer) ratio of pulverized coal concentration	γ	–	2

In Fig. 4, because of difficulty in ignition for WH, the temperature level on the burner axis is generally lower than that with burning HL coal. Igniting hard coal requires swirl burner induce more hot gas to heat and burn the coal particles. The traditional method is to adjust the air distributions for achieving the goal of increasing reverse flow. It can be found that with M increasing, the gas temperature level on burner axis ascends in some extent as Fig. 4 shows. In this experiment, the ISA flaring angle β plays a significant role in improving the temperature level on the burner axis. For example, when $M = 6.09$, the condition of $\beta = 35.5$ holds higher temperature level in the vicinity of the burner than other conditions. When $M = 2.71$, the condition of $\beta = 31.7$ shows the best ignition performance of all. It indicates that a suitable ISA flaring angle varies with different air distribution. The method by integration of ISA flaring angle and air distribution can improve the ignition performance of low-rank coal effectively.

For comparing ignition characteristic impacted by M, β and coal type, we selected the gas temperature in the vicinity of the burner as ignition temperature to discuss ignition situations in Fig. 5, because of the difficult determination of particle ignition. The ISA flaring angle range is marked with shadow, in which the enough high ignition temperature is ensured and little impacted by air distribution variation. Through both air distribution and ISA flaring angle variation, a wider adjustable range of ignition temperature can be achieved as the double sided arrow shows. It indicates the gas temperature near the burner can be controlled and improved more effectively.

β_{opt} is defined as that which makes ignition temperature highest under a certain air distribution condition. Fig. 6 displays β_{opt} variation with M. With increase of M, the β_{opt} is enlarged. The swirl ISA requires suitable flaring angle to develop expanding air, and outer secondary air is also guided by ISA flaring. Therefore, ISA flaring angle significantly affects secondary air flow characteristic and reflux effect. Low-grade coal (WH) calls for larger ISA flaring angle β than high-grade coal (HL).

3.2. Impact on coal combustion process

The temperature distributions in the furnace height direction are compared. Fig. 7 displays the results with burning HL coal. Generally, the gas temperature rises up in the lower furnace, and drops down gradually in the upper furnace along the furnace centerline. The air distribution shows a significant impact on the main combustion zone. When $M = 6.09$, the main combustion

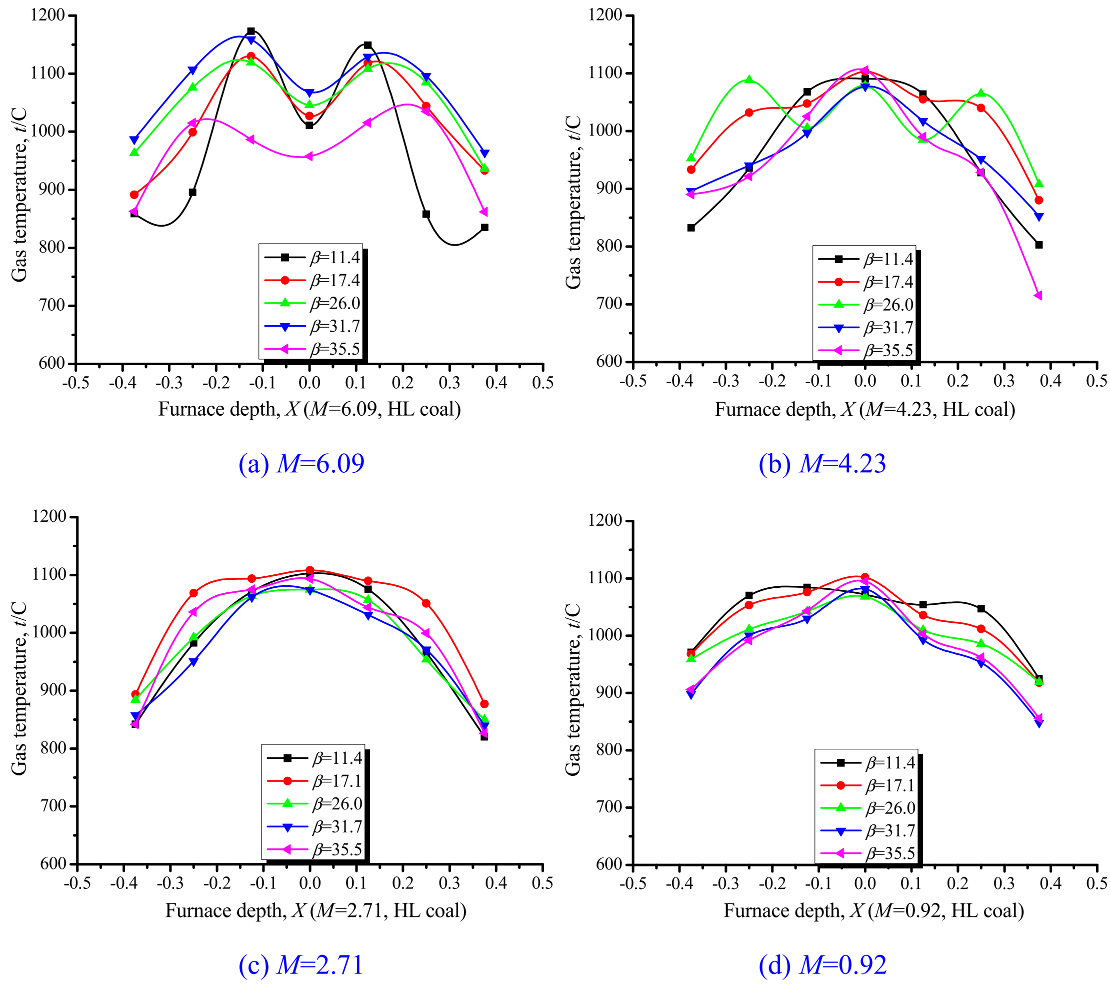


Fig. 3. Temperature on the burner axis (four air distribution conditions, HL coal).

happens early near $Z = 0.5–0.8$. With decreasing M, the temperature peak moves upwards gradually from $Z = 0.8$ to $Z = 1.0$. Meanwhile, β affects the temperature level along the centerline. When $M = 2.71$, 4.23 and 6.09, the conditions with large β holds high gas temperature in the combustion process. When $M = 0.92$, the condition of small β shows high temperature level.

Comparing to the results with HL coal, the gas temperature peak appears later and higher with burning WH coal as Fig. 8 shows. WH coal burning requires larger ISA flaring angle to reach high temperature level than HL coal. The impact of M and β mainly reflects in the lower furnace where coal ignited and fiercely burns. The gas temperature distribution in the upper furnace has similar variation at the stage of burnout.

For comparing combustion intensity, the maximum of T along the furnace center (T_{max}) is extracted and drawn in Fig. 9. There are different impact rules of β on T_{max} under different air distributions. For HL coal, the condition of $\beta = 31.7$ holds the highest T_{max} on the conditions of $M = 2.71$, 4.23 and 6.09. Under these conditions, T_{max} first rises then falls with β increasing. If $M = 0.92$, T_{max} keeps high level in the range of small β. It can be concluded that the condition of high M requires large β, and the condition of low M needs small β for enhancing combustion.

For WH coal, large β could not promise a high level of T_{max} on all air distribution conditions. Each air distribution has a corresponding flaring angle to realize the highest T_{max}. Under case of $M = 6.09$ the inner secondary air ratio is largest of all cases. When the inner secondary air flaring angle β is small, the swirling effect of inner secondary air will be limited by the flaring. The recirculation zone is also weakened which goes against ignition and combustion later. The secondary air would mix with primary air and coal earlier, which increases the ignition heat of pulverized coal stream. The spout area of outer secondary air appears large. The jetting effect is reduced so as to weaken the turbulence and mixing in later period. Therefore, with enlarging β the T_{max} generally increases.

In other cases, the inner secondary air ratio becomes less. When β rises up over some value, the axial velocity of the swirl inner secondary air decays sharply and the tangential velocity expands fully in the radial direction. The outer secondary air momentum becomes strong. Both the factors cause open flow easily outside the burner which leads to inflection point for T_{max} along the furnace centerline with β variation in other cases.

It can be seen from Fig. 9 (b) that a small flaring angle β should be avoided because of its corresponding low level of T_{max} on all conditions. The condition of small β prejudices WH coal ignition as mentioned in section 3.1, thus the later stage of combustion is affected negatively.

3.3. Impact on gas species and emissions

The influence of ISA flaring angle on gas emission is mainly concerned in this section. Fig. 10 compares CO emission of all study

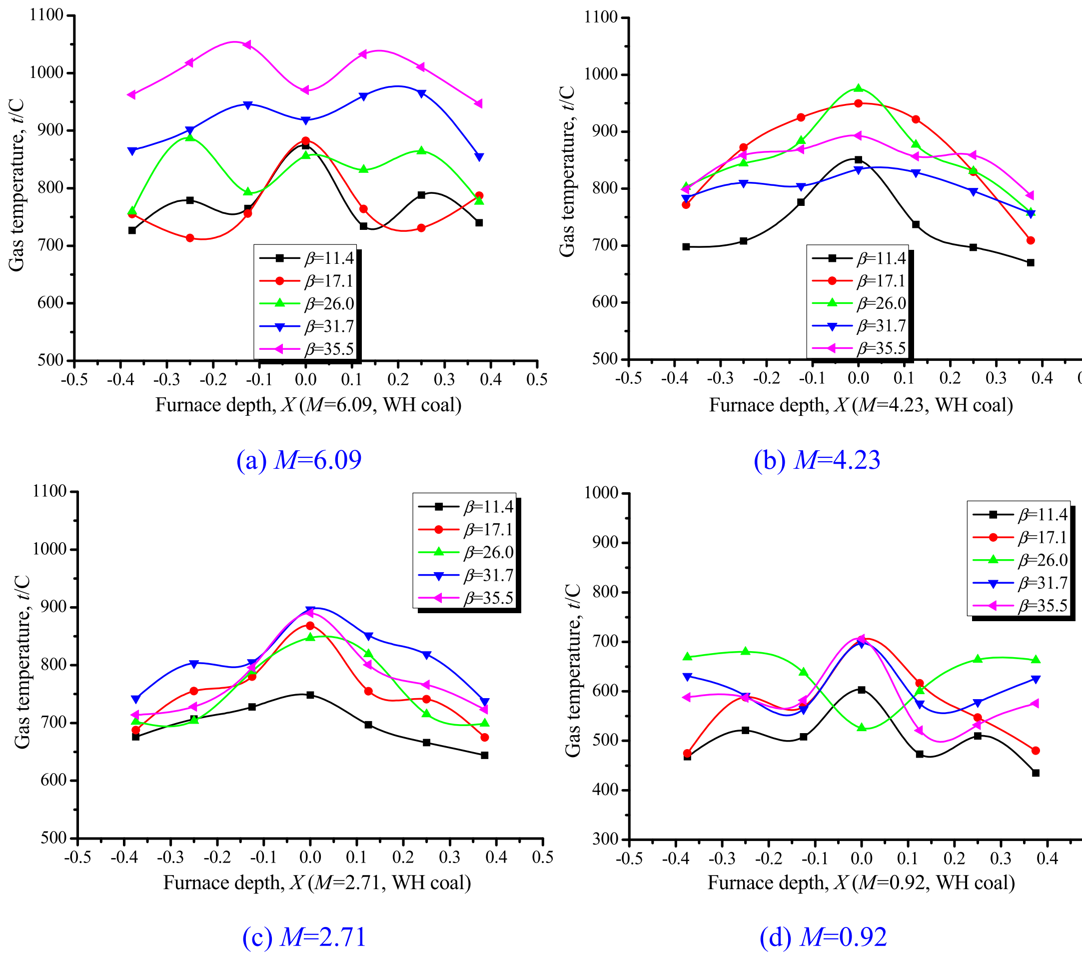


Fig. 4. Temperature on the burner axis (four air distribution conditions, WH coal).

conditions to discuss the chemical uncompleted burning heat loss. For HL coal, large β (31.7–35.5) is recommended to reduce CO emission on the conditions of $M = 6.09/4.23$. If M decreases to 2.71/0.92, the suggested β should be reduced to 26.0–31.7. Because HL coal is easy to ignite, the mixing between fuel and air in the later period is dominant in chemical uncompleted burning process. The suggested β responding to M balances reflux feature in the ignition period and mixing characteristic in the char burning stage. When burning WH coal, large ISA flaring angle is required to help the low-rank coal burning effectively. CO emission is reduced to minimum with $\beta = 31.7$ on all air distribution conditions. Through integration of flaring angle β and air distribution M adjustment synergistically,

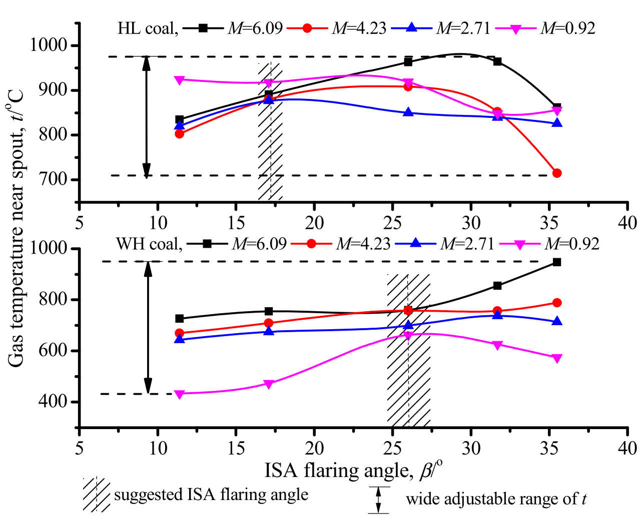


Fig. 5. Ignition characteristic compare.

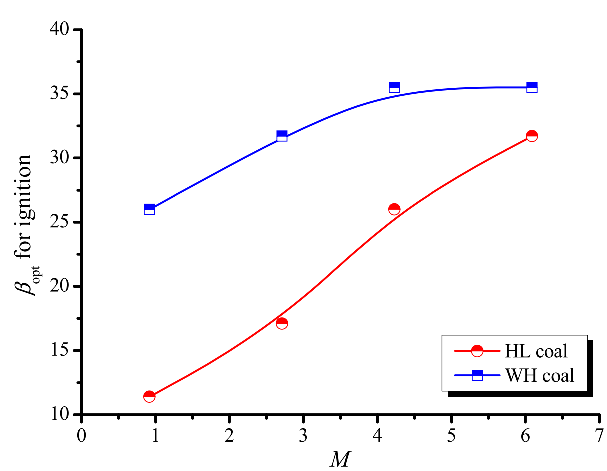


Fig. 6. Optimal flaring angles as function of M.

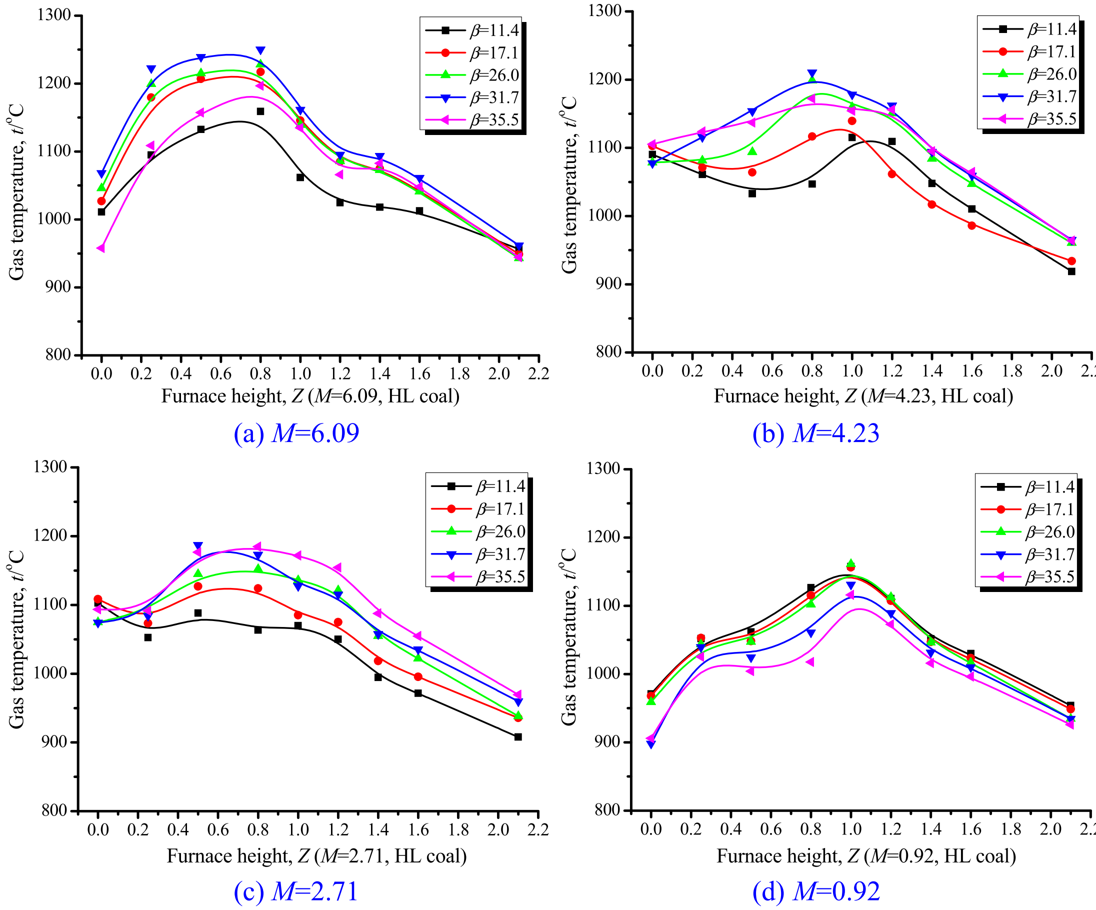


Fig. 7. Temperature distributions along centerline (four air distribution conditions, HL coal).

it is believed that the chemical uncompleted combustion loss can be controlled to the minimum.

Fig. 11 compares NO_x emission for all conditions. When burning HL coal, the maximum of NO_x emission happens on the conditions of medium ISA flaring angle β. The reasons are inferred as follows. The gas temperature in lower furnace is limited with small β. And oxygen supplying from the secondary air for coal is delayed with large β. Both the situations mentioned above control the NO_x emission in the combustion process.

When burning WH coal, the variation of NO_x emissions influenced by β is similar to that with burning HL coal. Medium β caused the maximum NO_x emission except the condition of $M = 0.92$. When $M = 0.92$, the NO_x emission achieves the minimum with medium β. It is probably because the combustion under this condition worsens the temperature level and causes low NO_x emission. This condition for WH coal should be avoided for combustion. If we add flaring angle adjustment to traditional air distribution regulation, it is believed helpful for further decreasing chemical uncompleted heat loss and NO_x emission.

3.4. Impact on char burnout

Fly ash was extracted by sampling probe at the outlet of furnace in the combustion experiment, and investigated by gravimetric determination method. Then the burnout can be calculated by the formula as follows [11].

$$\psi = \frac{[1 - (w_k/w_x)]}{(1 - w_k)} \tag{2}$$

where ψ is the char burnout, w is the ash weight fraction, and the subscripts k and x refer to the ash contents in the input coal and char sample, respectively.

From Fig. 12 it can be seen that both M and β influences the burnout significantly. The burnout of WH coal is lower than that of HL coal. For both HL coal and WH coal, there is an optimal β on each air distribution condition for highest burnout. It can be inferred that small β affects ignition negatively, and overlarge β easily leads to open air flow. A suitable flaring angle assures not only enough hot gas reflux for ignition, but also mixing turbulence ability of secondary air in later periods. The optimal β becomes smaller with M decreasing for HL coal burning, but enlarges for WH coal. It is suggested to match ISA flaring angle of burner with air distribution variation. The burner flaring angle adjustment further enhances burnout and strengthens coal adaptability for burner.

4. Conclusion

In this paper, we propose a novel swirl burner with adjustable inner secondary air flaring angle, which can be operated combining with air distribution to improve burning effectively. Through opposed wall fired experiment, the effect of this novel combustion regulations are analyzed.

With the variation of β, temperature in the vicinity of burner can be adjusted in a wide range. WH coal ignition requires larger β than HL coal. The influence of ISA flaring angle β on burning is closely related to air distribution conditions and coal. For HL coal, large β is recommended on conditions of high M, and small β is suggested on

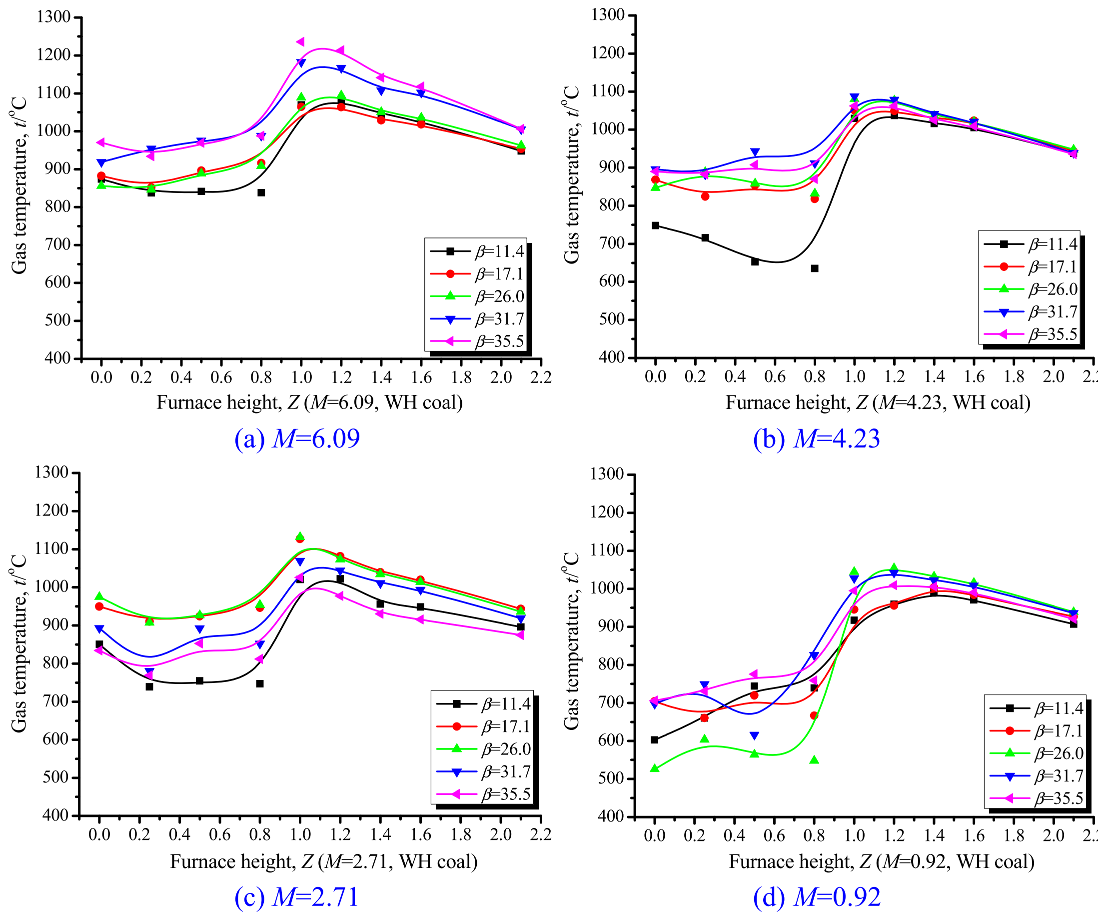


Fig. 8. Temperature distributions along centerline (four air distribution conditions, WH coal).

condition of low M. For WH coal, small β should be avoided on all conditions.

ISA flaring angle β of burner affects emissions in some degree. Large β helps decreasing CO emission Medium β easily leads to high NO_x emission. Increasing β can partly realize staged combustion for swirl burner to control NO_x emissions.

Burnout is affected by coal type, air distribution M and inner secondary air flaring angle β. The recommended β reduces a little with M decreasing for HL coal, and keeps large value under different air distributions for WH coal. In conclusion, integrating β and M variations helps combustion organization more efficiency and cleaning with wide adaptability of coal in this experiment.

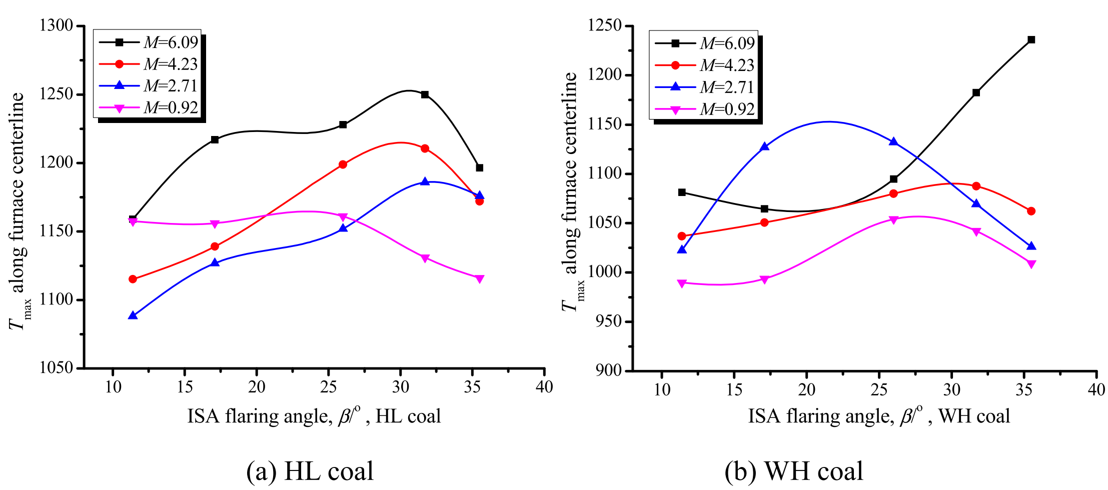


Fig. 9. T_{max} along furnace centerline.

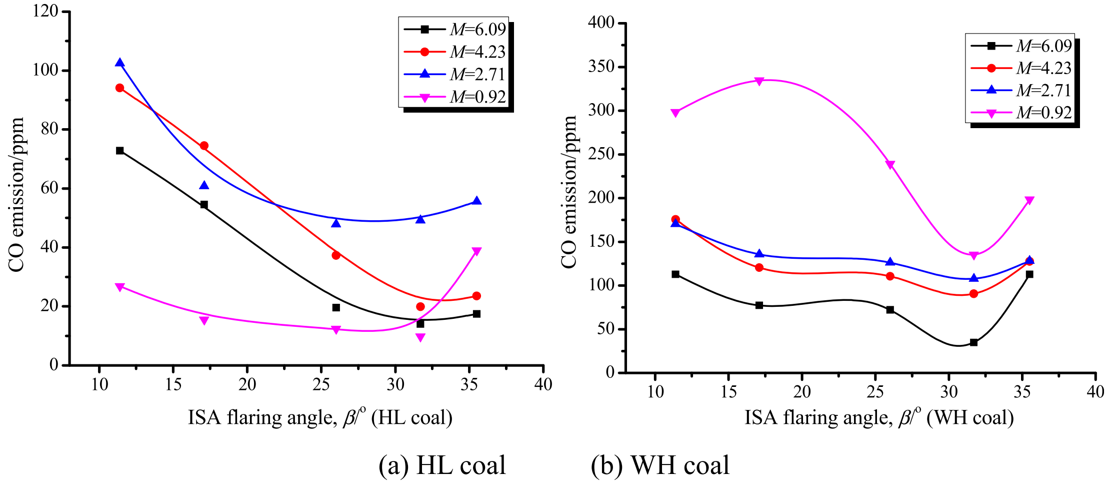


Fig. 10. CO emissions compare.

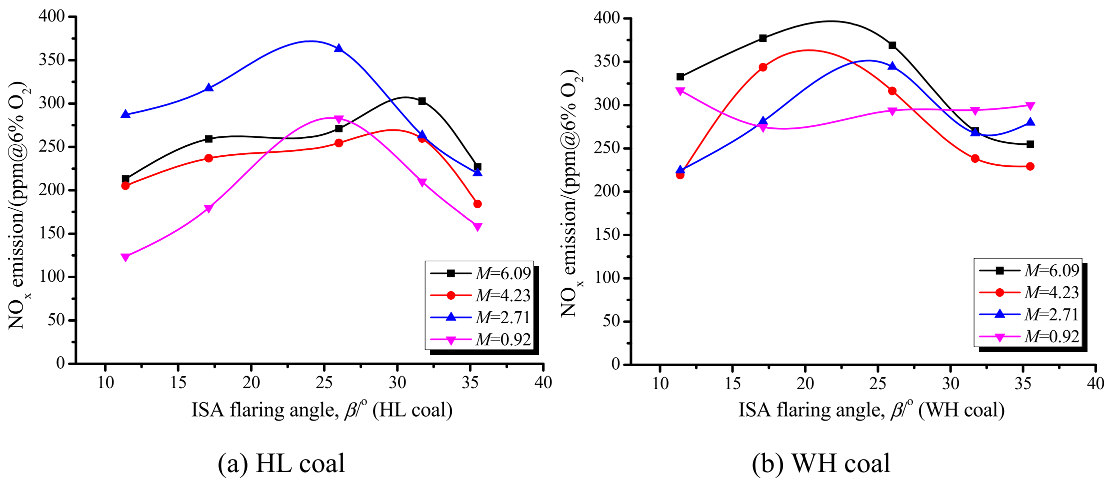


Fig. 11. NO_x emission compares.

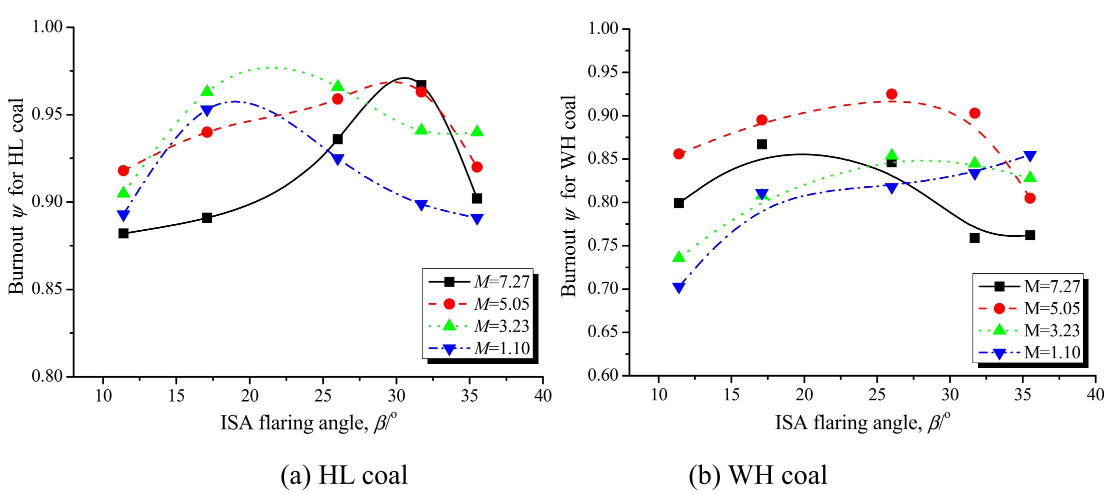


Fig. 12. Burnout compare.

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